14 Million Hours of Operational Experience on Phosphate ester Fluids as a Gas Turbine Main Bearing Lubricant.

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Abstract: Phosphate ester fluids have been used as a gas turbine main bearing lubricant for more than 35 years. Acid treatment systems utilizing Fullers' Earth or Activated Alumina have been used to remove acids produced during the PE fluid degradation process on an intermittent or continuous basis. Both acid adsorbing medias contribute metal soaps during the acid adsorbing process. Over time, the build-up of metal soaps significantly reduces the capability of the media to adsorb acids. The end result is escalating acid levels and fluid operating problems.

The introduction of ion exchange as an acid adsorbing media has eliminated the catalytic fluid degradation process, and offers phosphate ester users' extremely long fluid service life.

Key Words: Fullers' Earth, Activated Alumina, Adsorbent, metal soaps, ion exchange.

Introduction: A large gas transmission pipeline has used phosphate ester fluid as a gas turbine main bearing lubricant for over 30 years. Fluid life was generally limited to 4-5 years. Fluid degradation caused numerous turbine and compressor bearing failures. About 20% of the turbine fleet experienced phosphate ester reservoir change-outs yearly. A thorough analytical investigation of 82 gas turbine phosphate ester reservoirs (5000-11000 liters) over a four year period yielded extensive data to redefine existing fluid maintenance procedures. Revised maintenance procedures and the introduction of ion exchange have eliminated bearing failures caused by degraded fluid, and extended fluid life in excess of 230,000 operating hours.

Phosphate ester Maintenance Practices

Prior to 1985, as demonstrated in Figure 1, standard maintenance practice for phosphate ester fluid as recommended by the fluid manufacturer's was to utilize Fullers' Earth media on an intermittent basis to control fluid acid levels between (0.50 and 0.30 TAN).

<u>See Figure 1 (Intermittent acid treatment)</u>

It is not the intention of this paper to discuss the fluid degradation process of phosphate ester fluids in terms of its chemical break-down, as the topic has been documented very well over the years[1]. The major influences on fluid degradation are; system design, introduction of metal soaps, changes in air release time, as well as oxidation and hydrolysis. Key factors contributing to the degradation cycle are shown in Figure 2[2].

<u>See Figure 2 (The Fluid Degradation Cycle)</u>

From a turbine operator's perspective, it is important to understand how the fluid degradation cycle impacts fluid maintenance, fluid health, and turbine operating problems associated with deteriorating fluid. To provide an example from a turbine operators perspective I will describe the fluid maintenance and operating problems of one reservoir that is typical of a gas turbine driven natural gas centrifugal compressor operating at a pressure of 8,000 KPa. Fluid reservoirs for these turbines are from 5,000 to 11,000 litres and would require approximately, 155 Kg. of Fullers' Earth media for fluid treatment.

I will comment on causes of fluid degradation that were established as a result of an extensive review of over-all reservoir health on the entire turbine fleet that was conducted in 1987 with the assistance of both fluid suppliers.

Referring back to Figure 1, we see that by-pass filtration was activated when TAN reached 0.5, and discontinued when TAN was reduced to 0.3. During the 1st year of operation on new fluid, Fullers' Earth cartridges were generally exhausted after two operational cycles through the media over a 3-month period, and four sets of cartridges were used during the first year. Cartridge costs are about 14% of reservoir value. There were no fluid foaming problems or unit operating problems related to fluid degradation.

By the end of the 2nd year fluid life cycle, a set of Fullers' Earth cartridges is exhausted in about 6 weeks. As many as 8 sets of cartridges were used during the 2nd year of fluid operation. Cartridge costs were about 28% of reservoir value. Some reservoirs require small amounts of anti-foam due to fluid foaming.

Here we see the first symptoms of fluid degradation. The 12 sets of Fullers' Earth cartridges that have been used to date to control fluid TAN are contributing sufficient quantities of calcium and magnesium so that fluid air release time is affected. Metal soaps are starting to deposit on the surface of the high pressure oil seals. Calcium and magnesium levels are about 50 to 90 ppm. Reduced seal clearances result in fluctuating seal oil pressure which causes additional foaming of the fluid, along with higher than

normal seal operating temperatures. Acid production rates are increasing due to heat and increased oxidation.

Normal fluid analysis i.e. TAN, viscosity, s.g., and water, would not highlight any fluid problems at this point, however, metals analysis, fluid resistivity, RBOT, and alcor deposition tests would all show signs of early fluid deterioration.

Fullers' Earth adsorbing capabilities are reduced due to fouling of the media with anti-foam, and foam build-up inside the filter housing.

By the end of the 3rd year fluid life cycle, TAN levels have exceeded 0.60, and cartridges are exhausted in 3 weeks. TAN cannot be lowered below 0.50, and cartridge costs are 40% of reservoir value. Anti-foam is frequently required due to significant reservoir foaming and compressor high pressure seal failures that are common. Some turbines are also experiencing "hot" bearings. Calcium and magnesium levels are as high as 300 ppm. There are signs of copper in fluid metals analysis due to corrosive effects of high TAN on copper core oil coolers. Copper is a catalyst in degradation of phosphate ester fluids, but only becomes significant when TAN levels are high.

By the end of the 4^{th} year fluid life cycle, TAN levels have reached 1.9 and Fullers' Earth cartridges are no longer capable of reducing TAN. Cartridge costs are about 56% of reservoir value and compressor high pressure seal failures are yearly. Turbine bearing failures are common before the turbine has reached its 24,000 hour life cycle. Fluid replacement is carried-out in conjunction with the turbine overhaul. Twenty percent of the turbine fleet is experiencing reservoir change-outs yearly. In 1985, Activated Alumina replaced Fullers' Earth as the acid adsorbent media on the turbine fleet.

Figure 3, reveals that even with consistent interrupted maintenance and increasing numbers of cartridge change-outs, the net change in TAN over the 2^{nd}, and 3^{rd} year fluid life cycles is still increasing. By the start of the 4^{th} year of fluid operation, the increase in TAN is very rapid.

<u>See Figure 3 (Average TAN over fluid life cycle-interrupted filtration)</u>

Figure 4[3] helps us better understand why TAN accelerates so rapidly during the 4^{th} year life cycle of the fluid.

<u>See Figure 4 (Oxidative Stability of TBPP)</u>

On reservoirs that had used Activated Alumina as the adsorbent media, severe foaming resulted when sodium levels reached about 90 ppm, indicating that the effects of sodium were much more significant than calcium and magnesium.

The extensive investigation that was carried-out on the turbine fleet also revealed:

- Water did not represent a problem as water levels were all below 200 ppm
- Viscosity changes were minimal
- RBOT tests of new fluid were 200 minutes, and by the 4th year, had reduced to less than 80 minutes
- Total metals content of a 4-year oil reservoir were typically 400 ppm
- IPPP reservoirs had significantly higher total metals and TAN than TBPP reservoirs

While this investigation was on-going, excessive turbine maintenance costs and extensive compression outage lead to a management decision to use mineral oil on turbine packages purchased after 1989.

As a result of the fluid investigation, the following changes were made:

- Continuous fluid filtration was adopted
- IPPP fluids were discontinued, and TBPP was used for fluid make-up
- Maximum TAN of 0.10 was set a new goal.

Over a two-year period it became apparent that the benefits of adopting continuous side-stream filtration was limited to reservoirs in good condition.

While operating on Activated Alumina treatment, it was observed that reservoirs with high metals and high TAN levels, i.e. metals >200 ppm, and TAN > 0.5, exhausted at least 5 times more cartridges than a reservoir with low metals and low TAN, i.e. metals less than 50 ppm and TAN less than 0.10.

One unique reservoir had a TAN of 1.6, with total metals of 40 ppm. This reservoir was brought back to a TAN of 0.10 using three sets of Activated Alumina cartridges. This case suggests that the high metals content experienced in many reservoirs have an impact on the ability of Fullers' Earth or Activated Alumina to adsorb acids.

In 1987, Selexsorb was introduced as an adsorbent media with new reservoir fills. As Selexsorb could not be used on degraded fluid without causing jelling problems, we still lacked a means of controlling TAN on degraded reservoirs.

In 1989, I received some early research that had been carried-out in Europe regarding the use of ion-exchange. After two years of research, I incorporated ion-exchange media into a cartridge format that would fit the existing acid treatment housings used on the pipeline system.

In 1991, ion-exchange was introduced at two Beta test sites in an attempt to rejuvenate reservoirs that had seriously degraded fluid. Reservoir sizes were 5,300 and 11,000 liters respectively.

Both Beta test sites utilized Hilco 6-pack housings using 11 inch by 19 inch cartridges. Initial cartridge configuration used 3 cation and 3 anion cartridges in each housing. Initial metals content of both test sites are shown in Figure 5.

See Figure 5 (Starting Metals Analysis)

Results of Test Site #1:

The first set of cartridges lasted approximately 150 hours. Figure 6, reveals that water content increased from 450 ppm to 1250 ppm, and TAN increased from 0.90 to 1.25. Figure 7, reveals that total metals are reduced from 480 ppm to 110 ppm during the same interval.

See Figure 6 (Tan vs. Water Test Site 1)
See Figure 7 (Tan vs. Metals Reduction Test Site 1)

It is important to note that while the first set of cartridges were in operation, water content peaked at 1250 ppm at 150 operating hours and then dropped back to about 185 ppm. Water evaporated from the main lube oil reservoir and power turbine bearing housing vents. The fourth set of cartridges installed were anion only.

Total metals content at the end of the test was about 50 ppm. Current metals content is less than 10 ppm.

Results of Test Site #2

Figure 8 shows that the first set of cartridges lasted about 48 hours. Metals content decreased from 285 ppm and TAN decreased from 1.15 to 0.75. It is interesting to note that we did not see the high TAN increase associated with cation resin because there were two Hilco housings utilized for this test site. The extra 3 anion cartridges were capable of removing the acids produced from the cation resin reaction.

See Figure 8 (TAN vs. Metals Reduction Test Site 2)

There is some confusion from site personnel as to the make-up of the second and third set of cartridges, however, it is clear that the fourth set of cartridges were anionic as TAN decreases quickly over an 1100 hour time period.

Figure 9 shows the increase in water production. It increases from 300 ppm with the first set of cartridges. Water content during the second and third set of cartridges suggests that the cartridges were not in continuous service. This could have been caused by blockage of the one-half micron post-filter, which was not replaced until the 4th set of cartridges were installed.

See Figure 9 (Tan vs. Water Test Site 2)

At both test sites, the short life of the first set of cartridges was caused by considerable fouling of the media from contaminants being removed from the fluid. Fouling of the half-micron post filter was frequent until the fluid had been brought back to good condition. Typically the first post-filter cartridge reached a differential pressure of 140 kPa within 24 hours, the second within 2-3 days, and the third lasted more than 6 months.

In figure 10, RBOT values for both test sites indicate that fluid recovery was quite significant. RBOT values were brought back to slightly less than 200 minutes.

<u>See Figure 10 (Fluid Recovery-RBOT)</u>

Fluid analysis from test site 1 revealed a "free phenol" content of 8,400 ppm. The second test site revealed a "free phenol" content of 4,300 ppm. This would lead us to conclude that the amount of phenols in the fluid do not impact the over-all health of the fluid or hinder the capabilities of the ion-exchange process.

Figure 11 shows a significant improvement in fluid resistivity after ion-exchange conditioning. Resistivity values increased from 5.6×10^9 to 12×10^9.

<u>See Figure 11 (Fluid Resistivity Improvement)</u>

To date, over 2,000,000 hours of ion-exchange experience has been achieved on this pipeline system, with TAN levels generally below 0.04. There are occasional "maintenance excursions", where TAN increases to .10, but these are rare and very temporary. Ion-exchange media has proven to have at least twice the life of Selexsorb on the 80 gas turbine packages. I qualify this by saying that Selexsorb used on these reservoirs with a TAN of 0.04 has a life of 6 months. Ion-exchange on an identical reservoir will have a useful life of 12 months.

In my experience, ion-exchange represents the best method of maintaining phosphate ester fluids in "near-new" operating condition. Fluid life can be maintained indefinitely. The youngest reservoir on the turbine system described is about 60,000 operating hours, and the older reservoirs vary from 160,000 to 235,000 operating hours. Figures 12 shows a typical reservoir analysis from a fluid vendor.

<u>See Figure 12 (Typical Fluid Analysis)</u>

Heavy Hydraulic Applications

I have gained considerable experience in the reclamation of phosphate ester fluids used in aircraft elevator lifting systems on Navy aircraft carriers. To date ion exchange treatment has been used on three aircraft carriers, recovering in excess of 50,000 gallons of fluid that was approaching the end of its life cycle. This unique application required an ion-exchange system of sufficient exchange capacity to handle 600 U.S. gallons-per-minute in one pass, unlike a turbine package that is on continuous side-stream filtration at a flow rate of 6 U.S. gallons-per-minute.

The single-pass application provides the means of eliminating any question as to when the media is exhausted. This question has led to significant debate in the by-pass filtration system that is typical of a gas turbine or EHC system. Some period of time elapses before the operator sees an increase in reservoir TAN, and comes to the conclusion that the media is exhausted.

Data from these projects has shown that the initial TAN of the fluid dictates water production. Furthermore, this unique application revealed the significant variation in acid removal rates due to variations in resin water content and fluid viscosity. With "un-dried" resin, total neutralization of the fluid is achieved in one-pass. When using resin from containers that had been opened for a few days, total neutralization did not occur in one-pass. Optimum resin efficiency that has been achieved to date is slightly less than 20% of that expected in the water treatment environment.

In this cold fluid application, vacuum dehydration was required, however, it quickly became apparent that water removal could not be accomplished to acceptable specifications in a single pass. Data from water tests[4] indicate vacuum dehydration efficiency in the order of 65% per-pass. The number of fluid passes required to remove water to specified values became a function of the initial TAN of the fluid being treated. Variations were made in fluid temperature to optimize resin efficiency and minimize pressure-drop across the resin vessels, but higher temperatures proved to reduce efficiency of the vacuum dehydration system.

New Phosphate ester Applications

In 1995, I initiated the development of a phosphate ester fluid to operate in the aero-derivative gas turbine engine environment. My experience in the gas turbine industry had shown that one of the current down-falls associated with the newer "second-generation" gas turbine, i.e. compressor pressure ratios greater than 20:1, was the limitations in thermal capabilities of the polyol ester oils currently being used (MIL-L-23699). A test was initiated for a trial of a TBPP phosphate ester fluid in a General Electric LM 1600 aero-derivative gas turbine. The test was initiated as a result of a number of coking problems associated with MIL-L-23699 oils. The fire properties of the phosphate ester fluid were also viewed as a significant advantage. In my opinion, General Electric has been very proactive by writing a test specification that allows the trial of a phosphate ester fluid in their LM series of gas turbines, LM1600, LM2500, LM5000 and LM6000.

To avoid the issue of water and ion-exchange for fluid maintenance during the fluid trial, Selexsorb was used as the adsorbent media. A standard 7" x 18" cartridge holding ¼ of a cubic foot of media was connected to the lube-oil supply header immediately down-stream of the main lube-oil filters. A post-filter of the same size was installed to insure Selexsorb media did not enter the lube-oil tank.

The test was discontinued due to a compatibility issue with the gas generator oil tank demister element which caused gas generator oil tank pressure differential to be exceeded, however, compatible elements have been procured, and the test will resume in the near future. A proposed phosphate ester trial on a Rolls Royce RB-211G is presently being reviewed between RR and FMC.

I am very optimistic that phosphate ester fluids will provide enhanced fluid performance on the newest second-generation aero-derivative gas turbine engines in operation today.

Conclusions

From a phosphate ester fluid user's perspective, ion-exchange eliminates the catalytic factors that contribute to the degradation process, i.e., metal soaps and air retention when using Fullers' Earth or Activated Alumina. If TAN levels are maintained at "near new " fluid values, the effects of hydrolysis and oxidation are significantly minimized. Ion-exchange offers the *"Total solution"* in the maintenance of phosphate ester fluids as it can rejuvenate degraded fluids, as well as maintain new fluids for an indefinite time.

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[1] W D Phillips and D I Sutton "Improved Maintenance and Life Extension of Phosphate Esters Using Ion Exchange Treatment" 10th International Colloquium Tribology Jan 96, Esslingen, Germany

[2] ibid.

[3] Oxidation Rate Study, Test Method 5308.6, Temperature @ 175°C @ Airflow rate of 5 L/hr for 100 hours

[4] Mr. Mark Mosley, Bremerton Naval Shipyard

Figure 1: Interrupted Oil Filtration

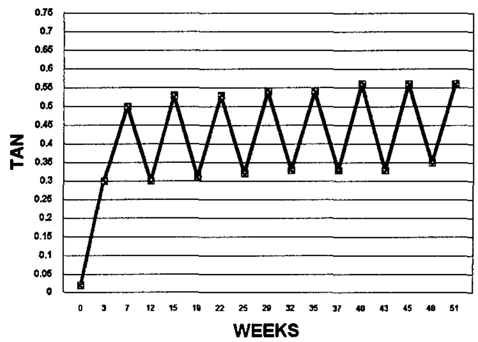

Figure 2: The Fluid Degradation Cycle

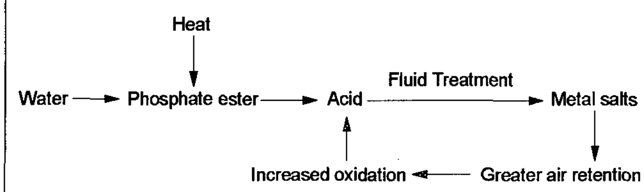

Figure 3: Average TAN over Fluid Life Cycle
Interrupted Filtration

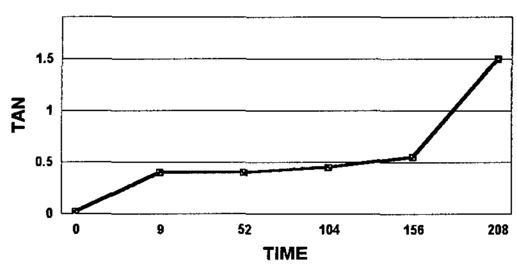

Figure 4: Oxidative Stability

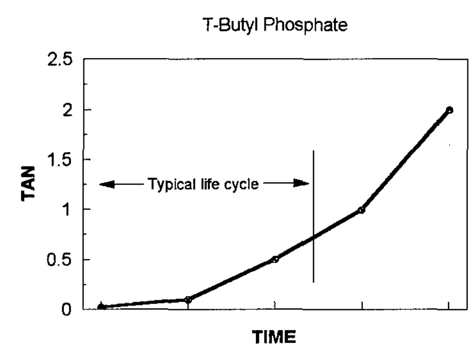

Figure 5: Starting Metals Analysis
Selected Test Sites

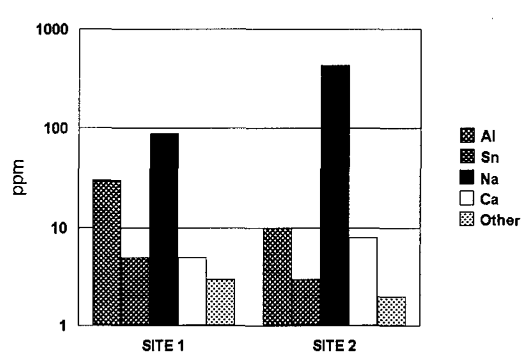

Figure 6: Tan vs. Water
Test Site 1

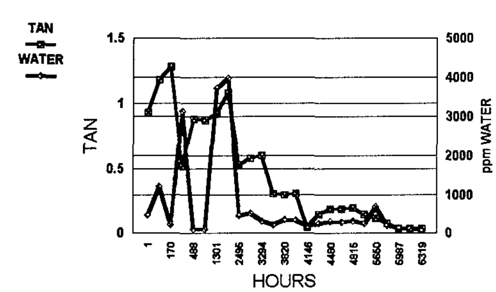

Figure 7: Tan Vs Metals Reduction
Test Site 1

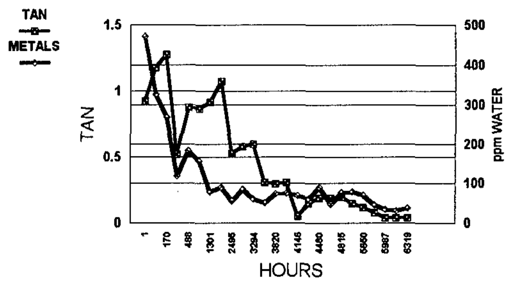

Figure 8: Tan vs. Metals Reduction
Test Site 2

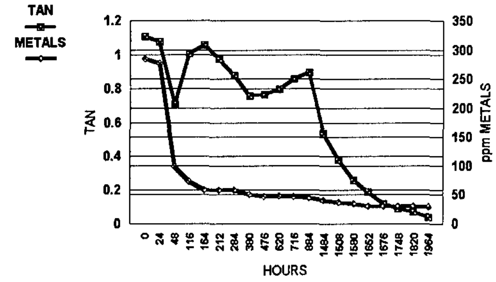

Figure 9: Tan vs. Water
Test Site 2

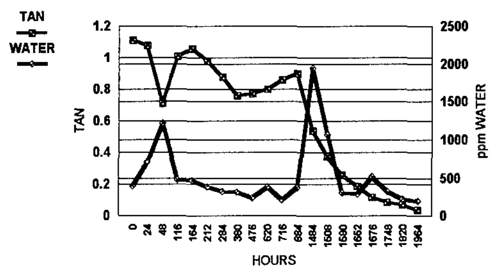

Figure 10: Fluid Recovery
RBOT Comparison

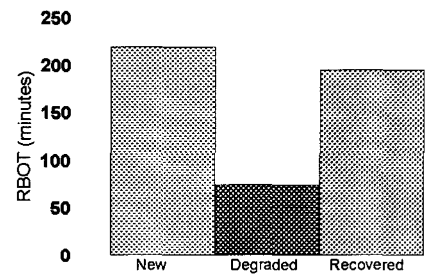

Figure 11: Fluid Recovery
Resistivity Comparison

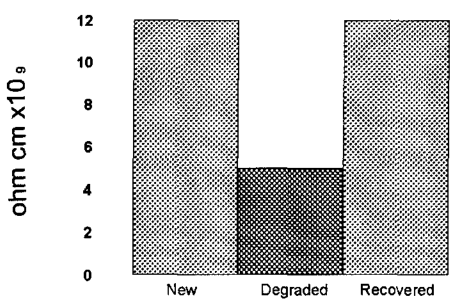

Figure 12: Typical Fluid Analysis

Recommended Limits		Min	Max
Oil Operating Hours	200,000+		
Acidity	0.07		0.10
Viscosity, SUS @100F	169	140	180
Specific Gravity @60F	1.17	1.14	1.18
Water Content WT%	0.01		0.1

Spectrochemical Analysis, ppm (Tested Bi-Annually)

Iron	0	Lead	0
Aluminum	0	Tin	0
Copper	3	Sodium	1
Chromium	0	Magnesium	2
Silicon	0	Zinc	0

TOTAL METALS 6 p.p.m.